Technical Progress Report

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For

Revolutionary/Unconventional Aeropropulsion Technology Evaluation through Thermodynamic Work Potential

A Revolutionary Aeropropulsion Concepts Program Research Initiative

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Progress Report, Activities May-July

Introduction

This report is intended as a status report for activities covered May through July 2002 under the auspices of NASA Glenn's Revolutionary Aeropropulsion Concepts (RAC) project. This is the first phase I quarterly report and as such, considerable focus will be given to defining the basic need and motivation driving this research effort. In addition, background research has been ongoing for the past several months and has culminated in considerable information pertaining to the state-of-the-art in work potential analysis methods. This work is described in detail herein. Finally, the proposed analysis approach is described, as are the various ancillary concepts required for its implementation.

Motivation and Objective

Transportation is a central element required in modern society. The ability to move goods and services from one place to another is absolutely vital to the function of societal commerce and continued advances will of necessity be linked to advances in our ability to transport goods quickly and inexpensively. Conversely, lack of growth in transport capability would choke societal advance, as transport is literally the lifeblood of society.

Advances in the transportation capability are in turn strongly linked to propulsion technology. Propulsion technology is an *enabler* with a powerful multiplicative force in terms of its potential impact on society at large. It therefore follows that it is in society's best interest to ensure continued and stable expansion of propulsion technology. It is this long-term and continuing need to advance propulsion technology that is the impetus for the work presented herein.

Although there is a real and ongoing need for continued propulsion advancements, one cannot dictate progress. Propulsion research and development is not a monolithic societal effort, but is rather a joint effort involving a diverse conglomeration of entities including academia, government, industry, and a variety of others. Each entity has a stake in the advancement of propulsion knowledge and acts semi-autonomously. A variety of ideas and viewpoints inevitably emerge from these various entities and it typically takes a considerable time for one technology to gain widespread acceptance.

The ability to quickly and easily identify the most promising propulsion technologies from amongst the myriad of concepts proposed would be useful. Although progress cannot be dictated, perhaps a method for identifying promising technologies would allow the pace to be quickened. The objective of this work is to develop methods to assist in the early identification and preliminary evaluation of propulsion technologies such that the most promising can be targeted for further development at the earliest possible time.

Current Need

History has shown that advances in propulsion technology are characterized by periods of incremental improvement in propulsion technology punctuated by periods of radical change to a fundamentally different and ultimately more capable propulsion technology than existed before. For instance, horses were superseded by the steam engine as a primary means of locomotion in the 19^{th} century. Steam engines were superseded by internal combustion engines, which have in turn been largely replaced by gas turbine engines for aircraft propulsion. Each of these technologies is a revolution in capability relative to its predecessor. Between these periods of revolution, the technology advances are incremental in nature and are relatively small departures from the existing technology base.

The advancement of propulsion technology could notionally be modeled as a series of s-curves similar to that shown in Fig. 1. This figure plots propulsion technological benefit on the y-axis with time on the x-axis. Each s-curve on this figure represents a given class of technology (steam, internal combustion, gas turbine, etc.). Note that each s-curve typically starts out at a level below the capability of its predecessor but rapidly increases in capability until some natural limit is approached. After the technology has matured for some indefinite period of time a societal impetus for further improvements in transport capability outstrips the technology capability and the stage is set for yet another revolution in propulsion technology capability.

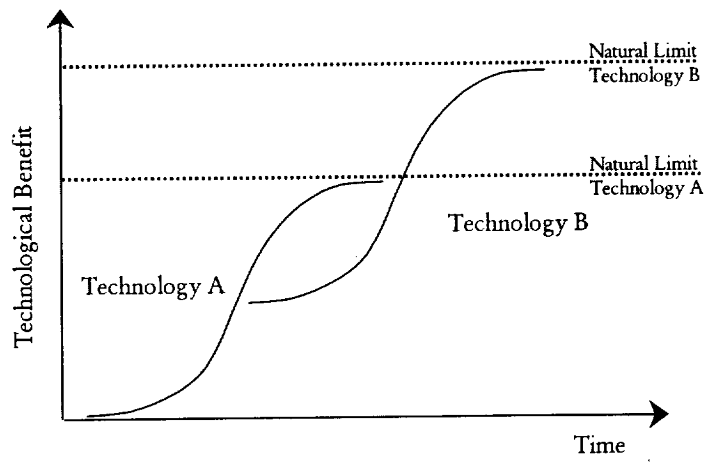

Fig. 1: Technology S-Curves

The gas turbine engine was the last major revolution in aerospace propulsion and occurred nearly 60 years ago. As gas turbine technology has matured, remarkable improvements in propulsion capability have been achieved. However, the cost of these improvements is steadily increasing as the basic technologies have matured. This is in turn leading to heightened interest in exploring revolutionary propulsion concepts that have the potential to become the next great improvement in propulsion capability.

The perception of gas turbine maturity in conjunction with a societal need for further improvement is prompting the expenditure of significant resources toward the exploration of revolutionary new concepts. This is driving a need for tools and methods to enable decision makers to more easily discern which concepts from a variety of possibilities holds the greatest promise to ultimately become the next great "propulsion revolution."

It is almost axiomatic that the best tools and methods available are inevitably those developed for analysis of the previous generation of propulsion technology. These tools typically have little or no usefulness for the analysis of revolutionary propulsion concepts that may be a significant departure from current technology. One is therefore forced to revert back to fundamental physics and build a suitable analysis model "from scratch" in order to discern performance potential for new concepts. This is a time-consuming (and sometimes costly) process. One would therefore like to devise a method that would allow an "apples to apples" comparison of disparate propulsion technologies without the need to build custom-made models for each concept.

It appears that there is a good basis for expecting this to be possible. After all, all engines operate within the same laws of physics and thermodynamics. Therefore, it should be possible to devise a generic model with a suitable level of abstraction as to allow it to be adapted to a wide range of concepts while retaining sufficient detail to allow direct comparison of concepts. This work seeks to address this need by devising a generic analysis method suitable for application to a wide variety of propulsion technologies and concepts. This method will enable disparate technology concepts to be compared on an equal footing in order to facilitate investment decisions.

Technology Identification, Evaluation, and Selection

Before proposing an approach to analysis of revolutionary aeropropulsion concepts, it is useful to review the current technology evaluation methods. There are a variety of these methods currently available today. The majority of these methods are rather ad-hoc and vary greatly from concept to concept. The most structured and versatile of these technology analysis methods is the Technology Identification, Evaluation, and Selection (TIES) method.* TIES has sufficient versatility to be applied to the analysis of virtually any complex technology or system. However, it has limitations to its usefulness as a method for evaluation revolutionary technologies. This section will explain the fundamental premise of the TIES method and discuss these limitations.

TIES is a methodology facilitating the identification of advanced technologies such as to provide for the greatest improvement over current state of the art when infused into the system under consideration. TIES is both general

* Described further in: Roth, B., German, B.J., Mavris, D.N., Macsotai, N., "Adaptive Selection of Engine Technology Solution Sets from a Large Combinatorial Space," Presented at the 37th Joint Propulsion Conference and Exhibit, Slt Lake City, UT, July 2001.

and systematic so that it can be applied to most any complex system. TIES forecasts the improvements in system level responses that would result from the infusion of individual technologies as well as combinations of those technologies. By comparing various technology sets based on their system level impacts, planners are better able to select the best technology set for further exploration. This is required because the costs of technology development are very high and continuing to increase for the foreseeable future. By directing funds into only the most promising technologies, resources can be more effectively used to advance the state of the art even in spite of the increased cost of incremental improvements.

$$R = \left(\frac{L}{D}\right)\left(\frac{V}{SFC}\right)\ln\left(\frac{W_f}{W_i}\right)$$

Measure of Aero. Tech. — Measure of Propulsion Tech. — Function of Mission + Structural Technology

Fig. 2 Breguet Range Equation Maps Aerodynamic, Propulsion, and Structural Technology Metrics to Yield Aircraft Range.

Fundamental Premise of TIES

The fundamental premise of the TIES method is that the impact of all technologies can be quantified in terms of changes in a few key parameters, the technology metrics. In the broadest sense, *a technology metric is a generic measure of technological capability*. For example, lift to drag ratio (L/D) is a good metric for aerodynamic technology capability for a given class of aircraft and specific fuel consumption (SFC) is a good metric for propulsive technology capability for a given class of engine. Both of these metrics directly impact aircraft range, fuel consumption, and endurance according to the relation shown in Fig. 2.

The central idea of the TIES method is that the impact of a given technology at the system level manifests itself primarily in terms of changes in technology metrics. Therefore, if an analytical relationship between technology metrics and system figures of merit (FoMs) is available, then one need only quantify technology impact in terms of changes in metrics, which can then be used to calculate overall performance. In the example above, the Breguet range equation is one such analytical relationship linking technology metrics to system performance: it describes range as a function of L/D and SFC.

The main advantage of quantifying technology impact in terms of technology metrics is that *once the relationships between metrics and FoMs have been created, the impact of any technology can be quickly and easily evaluated without the need to create an explicit model of the specific technology*. Instead, the delta in technology metrics can be determined (usually with reasonably high accuracy) through expert opinion and/or analysis. These deltas in technology metrics are essentially a compact embodiment of the technology model. The result is an analytical tool that uses a blend of analysis and expert opinion to yield a highly cost effective, timely, and flexible means of evaluating multiple technology impact.

The TIES Framework

The general steps in the TIES method are shown in Fig. 3, and a detailed description of the entire TIES method is provided in Ref. 1. Although TIES includes formalized processes for identifying technology need, the focus of this study is the last two steps of the method: evaluating and selecting technology combinations that create a feasible or viable design space. The steps of the TIES method that are pertinent to this study are:

Steps 1-2: Determine the system responses (or FoMs) of interest and key technology metrics through which the impact is modeled

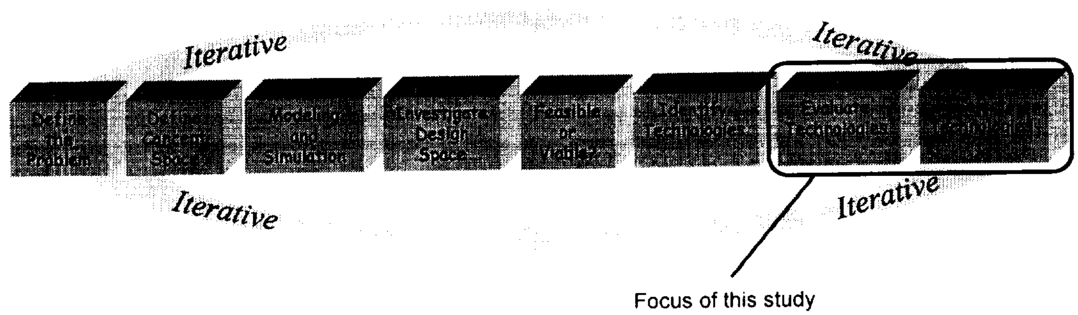

Fig. 3 Steps in the TIES Method (Adapted from Reference [3])

Step 3: Use analysis tools/models to create metamodel relationships linking technology metrics to system performance FoMs (the technology impact forecasting environment)

Step 6: Map technologies to deltas in technology metrics

Step 7: Evaluate the technology combinatorial space to identify the most promising combinations

Step 8: Use this information to select the appropriate technology combination

The system physics are modeled in step 3, creation of the Technology Impact Forecasting (TIF) environment. TIF is the technology evaluation engine used to evaluate the impact of technologies. It is nothing more than a set of analytical relations mapping technology metrics to system-level figures of merit. These relations can take the form of a computer program such as a mission analysis routine, a CFD code, or a linked system of programs. Therefore, TIF is the embodiment of several computational models of the complex system (a simple example of such a model is the Breguet Range Equation).

If the computation time/cost of evaluating complete analytical models is prohibitive, it is often desirable to create a metamodel (such as a response surface equation, RSE) which captures the essence of the complex analytical model while still being inexpensive to evaluate. The use of metamodels allows the TIF environment to be implemented in a very compact form using a standard statistical software package. Moreover, some of these packages provide interactive graphical depictions of the system responses to the technology metrics, which can be useful in answering "what-if" questions. Details of this method are given in Refs. 4 and 5.

Expressed in mathematical terms, one can think of the technology selection problem as consisting of an abstract space having *m* dimensions, each dimension representing a technology metric. If the impact of each technology manifests itself as a delta in these technology metrics, then we can think of a technology in an abstract sense as a *vector* of technology metric deltas that moves the state-of-the-art from some baseline datum out to a new level of capability. Some of these vectors may only take discrete lengths (i.e. a technology that is either "all" or "nothing"), while some technology vectors will have a continuum of admissible lengths. Some of these vectors are orthogonal to one another (i.e. independent), whilst others are not orthogonal (mutually exclusive options are such an example).

TIES Applications for Revolutionary Technologies

The strength of TIES lies in the fact that it uses physics-based modeling to forecast the system level impact of infused technologies on an existing system. TIES provides for the modeling of advanced technologies by identifying the projected improvement or degradation each technology has on various disciplinary metrics. The projected changes to these disciplinary metrics are then applied to a baseline concept, which is then analyzed using physics-based analysis and simulation tools. A metamodel is then created to capture the relationship between the disciplinary metrics, and thus the technologies, to the system level responses of interest. The impact of technology combinations on system level responses can easily be visualized through a graphical mapping of these system level responses to the presence or absence of each technology on the system in consideration.

Unfortunately, TIES is limited by the fact that it is predicated upon the existence of a detailed technology baseline from which technology perturbations can be made. TIES assumes that the impact of each technology can be characterized via its impact on a few key technology metrics. However, the perturbations on these technology metrics are usually limited to small deviations from the baseline due to model limitations. For example, presume that increase in turbine inlet temperature is a key technology metric used to estimate technology impact. The baseline model presumes a given turbine inlet temperature and the turbine cooling system, mechanical design, fan system, and so on is configured based on this level of technology. If a new technology were introduced that allowed a 1,000 F increase in allowable TIT, the results obtained from such a model would be useless unless the rest of the engine components were redesigned to be consistent with this increase in capability. Revolutionary concepts often require large changes to the state of the art, thereby limiting the usefulness of the existing TIES methodology without a parametric model capable of extremely large deviations from the baseline.

A second limitation of the TIES method is that it facilitates comparison of technologies within a single class of propulsors, but does not facilitate comparisons between classes. For instance, TIES is excellent for comparing the benefits of various technologies as applied to a gas turbine. A TIES model could also be used to compare the merits of those technologies applied to internal combustion engines. However, TIES does not facilitate comparisons of technologies between gas turbines and internal combustion engines. Thus, a methodology is required capable of simultaneously assessing vastly dissimilar, revolutionary technologies.

The need for a method to sift through revolutionary concepts is the centerpiece of this project. The objective is develop a method similar to TIES in that it would provide for the systematic evaluation of technological advancements using physics-based analysis; however, rather than incremental technological advancements, this new method would serve to project system improvements as a result of considerable or revolutionary technological advancements. It is expected that this new method will rely on forecasting the theoretical natural limitations that will ultimately determine a concept's future potential. These limitations in conjunction with the projected technical difficulty of approaching these limits will provide the basis on which dissimilar concepts are discriminated.

The Concept of Thermodynamic Work Potential

In order to analyze, evaluate, and ultimately compare dissimilar revolutionary propulsion concepts, a common Figure of Merit (FoM) is required such that this comparison can be made on a level playing field. Most current propulsion system FoMs rely heavily on thermodynamic efficiencies; however, these efficiencies can be, and generally are, defined uniquely for different propulsion systems and on a one-to-one basis do not provide a meaningful means of discrimination between systems. Whereas, work potential methods provide a foundation on which a universal FoM can be defined enabling an "apples to apples" comparison between highly dissimilar systems. Thus, ideally suited for the development of a revolutionary TIES methodology.

A General Definition of Work Potential

The idea of work potential is a concept that all people naturally intuit. It has been understood for centuries that a rock at the top of a hill has more work potential inherently stored in it than does one at the bottom. Over the centuries, mankind has learned to utilize the work potential stored in his environment to power sailing ships, drive windmills, transport goods, conduct business, etc. Yet although it is an easily intuited concept, a formal definition of work potential eluded scientific inquiry for centuries. It is only recently that the general concept of thermodynamic work potential has become a precisely (scientifically) defined quantity.

In the broadest sense, that which we think of as work potential is thermodynamically related to equilibrium (in a physical, chemical, thermal, or any other sense). Specifically, the *farther a given substance is out of equilibrium with its environment, the greater its potential to do useful work*. The higher a rock is on the hill, the more work can be extracted in taking it to the bottom of the hill. The stronger the wind blows, the more energy can be extracted in decelerating it relative to the ground. It is the constant state of non-equilibrium that drives the world around us. Today, we know this concept as the second law of thermodynamics, and the analytical techniques developed to quantify work potential are referred to as second-law methods.

A substantial body of work has appeared in the past several decades dealing with second-law approaches to measuring work potential and loss thereof. One such approach is the exergy concept, which has been applied to the gas turbine cycle by several authors, notably Clarke and Horlock,[6] who applied it to a simple turbojet example and showed where the most significant exergy losses were occurring. It is the best-known and most formalized method to estimate the magnitude of losses relative to a thermodynamically ideal process,[7,8] and first appeared in the United States due largely to the work of Keenan in the 1940s.[9] Put simply, *exergy is a thermodynamic state describing the maximum theoretical (Carnot) work that can be obtained from a substance in taking it from a given chemical composition, temperature, and pressure to a state of chemical, thermal, and mechanical equilibrium with the environment*. The general definition of exergy is given by:

$$Ex \equiv H - H_{amb} - T_{amb}\left(S - S_{amb}\right) + \left(\text{Other Terms}\right) \quad (1)$$

In this case, the "other terms" are used to denote exergy due to kinetic energy, potential energy, chemical potential, radiation, heat transfer, etc. Note that while energy is a conserved quantity, exergy is *not*, and is always destroyed when entropy is produced. Note also that the definition of exergy depends on the ambient environment. A considerable body of literature exists describing the theory and application of exergy analysis, and references 10, 11, 12, and 13 are standard texts on the subject.

Another work potential FoM that has been proposed in the past is gas horsepower (of isentropic expansion), which is used by Nichols[14] as a universal figure of merit for combustor loss. It is also used extensively as a figure of merit for gas generator power output, but has received little attention beyond this limited application. A third figure of merit was proposed by Curran and Craig[15] based not on energy, but force (thrust), known as the stream thrust concept. This involves calculation of stream thrust potential (also known as specific thrust) at each flow station and optimizing the cycle to deliver the highest stream thrust potential. Later, Riggins[16] extended this concept by introducing the 'lost thrust method' which allows accurate calculation of stream thrust loss due to inefficiencies. In addition, he introduced the thrust work potential and lost thrust work potential figures of merit and showed that optimization of exergy output does not necessarily lead to the best propulsive cycle from a thrust production point of view. Finally, Riggins suggested a modified definition of exergy, which he termed "engine-based exergy," and showed that this modified definition yielded results identical to those obtained through stream thrust methods.

Literature Review—Thermodynamic Work Potential

Before proceeding into outlining the current work and research being conducted in the area of exergy-based analysis and methods there are several noteworthy references providing a fundamental basis and background of exergy concepts. "Fundamentals of exergy analysis, entropy generation minimization, and the generation of flow architecture" by Bejan outlines some of the basic concepts of thermodynamic optimization through the minimization of exergy destruction.[17] "A Work Potential Perspective of Engine Component Performance"[18] and "A Comparison of Thermodynamic Loss Models Suitable for Gas Turbine Propulsion: Theory and Taxonomy"[19] provide a basic understanding of exergy analysis as directly applied to propulsion analysis. "A Generalized Model for Vehicle Thermodynamic Loss Management and Technology Concept Evaluation" proposes a general, exergy-based methodology for construction of loss management models.[20] One should also note that the terms exergy and work potential are often used interchangeably. Each of these references is available electronically on the Internet.

Work pertaining to exergy over the past few years has primarily focused on applying existing analysis methods to a much broader range of problems rather than extending the capability of the methods themselves. With increasing popularity exergy-based methods have found applicability in such diverse fields and disciplines as ecology and environmental impacts, economics, resource allocation within society, sustainable development,[21] as well as the obvious energy generation system design,[22] propulsion system design, and even overall vehicle design.[23] Despite the wide range of applicability of exergy-based analysis, there, as of yet, seems to be little commonality in the manner or methods in which such analysis is conducted. Little work has been directed towards the development of a standardized method formulated in such a way as to allow the analysis of highly disparate systems.

Not only have exergy-based methods gained popularity across these diverse fields and disciplines, but they are also beginning to grow in applicability within each field. For instance, within the discipline of propulsion system design exergy-based methods have been used to analyze various systems identifying major loss components. Exergy-based analysis methods are beginning to be used throughout the entire design process showing potential applicability at the conceptual, preliminary, and detailed phases of design as well as operations support and system improvements following production. The current expressed need is for a unified methodology capable of analyzing a particular system at these various levels of abstraction from a performance perspective and also economic, safety, reliability, and investment risk perspectives. Developing such a method would be one of the primary objectives of Phase II. The objective of Phase I is the development and demonstration of a method providing for the comparison of various propulsion alternatives based on the relative performance capability of each alternative at the conceptual level.

From the performance perspective various energy systems have already been analyzed using exergy-based methods. Such systems have included fighter aircraft,[20] hypersonic vehicles,[24] various gas turbine cycles, scramjets,[25] and even fuel cells.[26] Although, generally each system analysis was conducted independent of one another and with little if any intent or means of comparing these systems to determine relative effectiveness. Thus, one of the primary objectives of the Phase I research is to develop a standardized method to facilitate such comparison of rather immature propulsion system concepts. One element of this process will inevitably be the development of a generalized method to determine the theoretical performance limits of systems under consideration. This also is an exergy analysis technique that has been previously utilized. One such example of an application of this technique was by Wright, David, and Haddow who used this technique to determine the upper limit to solar energy conversion.[27] However, no standardized method exists to facilitate the calculation of the upper limits of multiple dissimilar systems for the purpose of comparison.

Another area of current research is the utilization of exergy analysis as the basis for design optimization techniques.[23] The foundation for many of these techniques is the identification of the theoretical limit, which is then used as the target for a particular optimization algorithm. Design parameters can then be varied in order to approach the specified theoretical limit. However, conventional exergy analysis has not yet provided a means for directly identifying the required alterations to optimize a particular system. The main focus of current research is directed towards developing a formalized method to best identify those parameters having the most impact on exergy destruction and then determining how best to modify them rather than just trying to evaluate each incremental alteration of each parameter and every combination thereof. Without more direct methods, exergetic optimization of complex systems becomes nearly impossible due to the dimensionality of such problems.[8]

One property of exergy seems to have the potential for resolving this dilemma or at least being a primary element of the solution. That property is associated to the concept of avoidable and unavoidable[28] exergy destruction, which in turn is related to the concept of useable versus unusable work potential. Both of these concepts deal with the idea that there are inescapable exergy losses associated with any system regardless of system modifications. As a result, it is futile to attempt to do so. Thus, by first clarifying which exergy destruction mechanisms are avoidable and unavoidable designers can better focus their resources and energies on those destruction mechanisms identified as avoidable. To facilitate this process a newly defined metric, the exergetic efficiency, is commonly proposed for the comparison of dissimilar system components and even systems themselves as it provides for a common "currency". Investment costs have also been linked to both avoidable and unavoidable destruction mechanisms, leading logically to the concept of avoidable investment costs.[29]

Despite the extensive research that is currently taking place in the area of exergy analysis and optimization techniques, it appears that there is little if any work currently underway to formulate a methodology for the purpose of propulsion system comparison. Most current research seems to be directed towards analyzing and improving various individual propulsion systems, although none directed towards determining the *relative* worth of these dissimilar systems especially in the early stages of development.

Proposed Analysis Method

The general approach suggested for analysis of revolutionary aeropropulsion concepts is illustrated in Fig. 4. The process starts with a definition of the fundamental concept and its principles of operation. Once the concept is defined, a simplified first-law analysis is constructed using a "building block" approach based on standard thermodynamic processes. This analysis is typically sufficient to obtain crude performance estimates for the concept under investigation. It is also a necessary prerequisite to the third step in this process. The third step is to construct a work potential model of this same concept to facilitate comparison to other concepts. This model is also used to define the absolute limits on the ultimate performance of such a concept. Finally, a more detailed mechanical design model is constructed and used to examine practical limits given current state-of-the-art technological capabilities. The focus of the phase I research in this project is primarily on the first three steps, with the last step being the subject of later research.

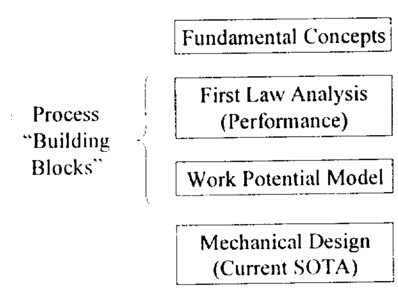

Fig. 4 General Approach to Analysis of Revolutionary Aeropropulsion Concepts.

As the immediate objective of this work is to explore applications for work potential concepts to analysis of revolutionary propulsion concepts, the third box shown in the Fig. 4 above is the focus of considerable research effort at this time. In particular, considerable effort is being expended to develop a propulsion system equivalent of the vehicle loss management models described in Ref. 20 and shown in Fig. 5.

The general methodology for construction of detailed loss management models is divided into four basic steps,[30] as shown in the flowchart of Fig. 5. In brief, Step "0" in the construction of a loss management model is to explicitly define loss in a way most suited to the needs of the current analysis. It was previously mentioned that are a variety of ways to measure thermodynamic loss, and the choice of which to use depends on the situation at hand. When this is known and clearly understood, the first step is to clearly identify all loss mechanisms that are significant to the operation of the vehicle. This is done with the assistance of a functional decomposition tool known as a relevance tree, and the ultimate outcome is a detailed listing of all sources of loss.

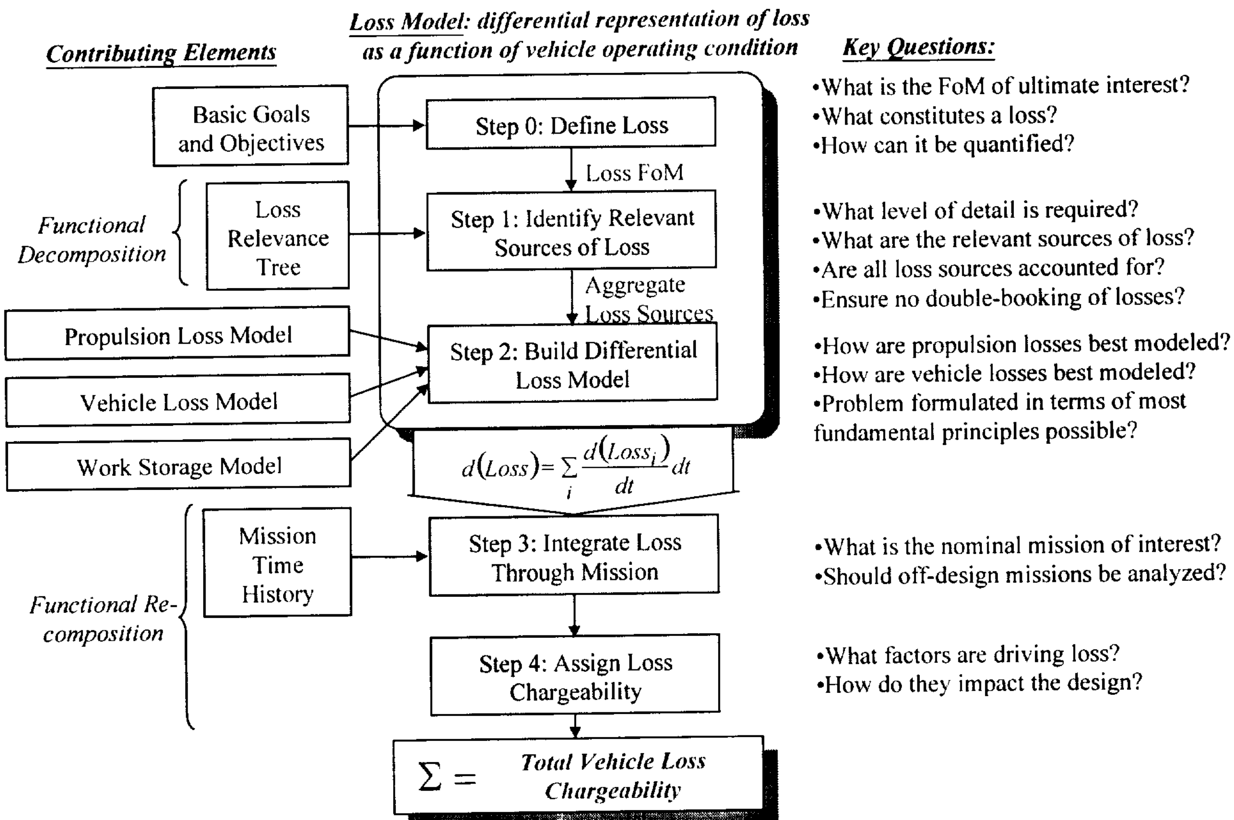

Fig. 5 General Methodology for Construction of Loss Management Models.

Next, a mathematical representation of each loss source is created in step two, which necessarily requires extensive information on propulsion system and vehicle systems performance. The result of Steps 0-2 is a differential loss model that describes the instantaneous loss breakdown of the vehicle as a function of operating condition. The construction of an accurate and complete differential representation of loss is an essential feature that enables the creation of vehicle loss management models.

Step 3 integrates this differential loss model through time over a single vehicle mission or duty cycle to obtain total loss chargeable to each loss mechanism. Obviously, it is imperative to use a vehicle mission which is representative of the operation that the vehicle will actually experience in service. Finally, one must assign chargeability for each loss to its underlying source. The objective of Step 4 is to allocate each loss to the factor(s) that drive it such that the true thermodynamic cost of each design decision can be understood.

Absolute and Practical Limits on Performance

The previous section mentioned the concepts of "absolute" and "practical" performance limits. An "absolute" limit is defined as one that is dictated solely by the laws of thermodynamics and physics. A typical "first order" cycle analysis of an idealized cycle often yields a result that is essentially an absolute limiting case on the best possible performance of a propulsive concept. A practical limit is defined less by laws of physics and more by the current state-of-the-art in technological capabilities (especially materials, computation, and so on). The latter is considerably more difficult to estimate accurately than is the former. Whereas the former can be reasoned based on first principles, the latter is a product of expert assumptions based on perceived technological limits that may or may not be significant barriers to progress.

This concept is of use in the analysis of revolutionary aeropropulsion concepts because it provides a ready-made division between analysis fidelity for revolutionary concepts. Moreover, this dividing line is a logical progression of analysis methods: definition of fundamental principles, followed by determination of absolute limits on performance, and finally, determination of practical limits on performance.

Fundamental Thermodynamic Processes

The number of thermodynamic processes that compose most cycles is relatively limited. It is possible that this will prove a valuable basis for developing general analysis methods for any conceivable thermodynamic cycle. If a limited number of generic processes can be modeled in "building block" fashion, it may be possible to use these building blocks in various combinations in order to model any possible machine.

The most common flow processes are adiabatic compression/expansion, constant pressure heat exchange, throttling (adiabatic pressure drop), velocity change via nozzle/diffuser, constant pressure combustion, and constant volume combustion, as shown in Fig. 6. These few flow processes collectively account for 80% of all practical engineering cycles. The remainder can be captured if one includes a few more (rather obscure) thermodynamic processes, notably constant temperature expansion/compression.

If each of these processes could be treated in the most general sense possible, it should be possible to "mix and match" the fundamental processes to construct any cycle imaginable. Moreover, if each of the flow processes is analyzed from a work potential point of view, it should be possible to construct a comprehensive and intuitive approach to analysis of thermodynamic performance for any general cycle.

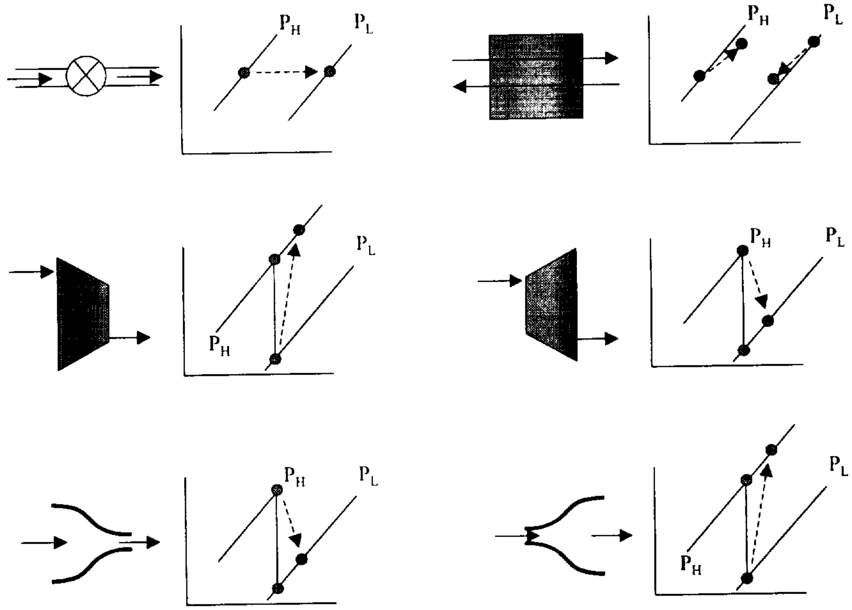

Fig. 6 Several Flow Processes Typically Used in Prime Movers.

Physical Realization of Propulsive Cycles

Analysis of thermodynamic performance is only a portion of the makeup of a propulsion concept. The utility and viability is also ultimately a function of not only thermodynamic performance, but also a variety of mechanical design issues that directly impact the feasibility of realizing the cycle in some physically realizable hardware. A prime example of this is the Carnot cycle. It is well known that the Carnot cycle produces the highest possible work in moving heat between two infinite heat reservoirs of differing temperature. However, knowledge of the thermodynamic cycle alone has not led to the creation of Carnot cycle machines. Although simple in theory, the constant temperature expansion and compression processes are exceedingly difficult to realize in hardware. Thus, the ideal heat engine cycle is not prevalent as a prime mover.

This aspect of revolutionary concept analysis is considerably more difficult to capture than are the strictly thermodynamic performance aspects. This is because the ability to realize a thermodynamic cycle in practical hardware is intimately linked with a myriad of mechanical design details. It is difficult or impossible to capture all possible mechanical design drivers in a single concise analysis environment, as there are simply too many possible drivers that may come into play.

One approach that holds promise for analysis of the ability to physically realize a cycle is to use mass-specific quantities as a basis for comparison with the current state-of-the art in propulsion technology. For instance, mass-specific flow rate is a good basis for comparison of a variety of machines. Mass-specific power output could perhaps be another useful figure of merit. This aspect of the present research will require considerable care if the final method developed is to be truly useful for any propulsive cycle.

Planned Research Activities—4Q02

Research activities planned for the next three months will focus on development of a comprehensive analysis method based on the general principles outlined herein. Emphasis will be given to developing a "building block" model for thermodynamic processes that will be generally applicable to any thermodynamic process. It is anticipated that the results of this work will then be applied to several revolutionary propulsive cycles, preferably including thermoacoustic propulsive cycles and pulse detonation devices. Significant elements of the basic work potential analysis method also remain to be developed, particularly those associated with calculating the work potential of nuclear reactions and of high-amplitude acoustic waves. These elements will be necessary to apply this technique to the analysis of propulsive cycles based on these phenomena.

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